MEG Calorimeter Experience and Upgrade

2012 Project X Physics Study

W. Molzon

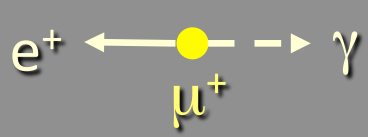
University of California, Irvine

- Calorimeter motivation from $\mu \rightarrow e\gamma$ experiment requirements
- The MEG liquid xenon calorimeter
- MEG calorimeter performance
- Improvements being considered

Signal and Background Signatures

Signal

$\mu^+ \to e^+\gamma$



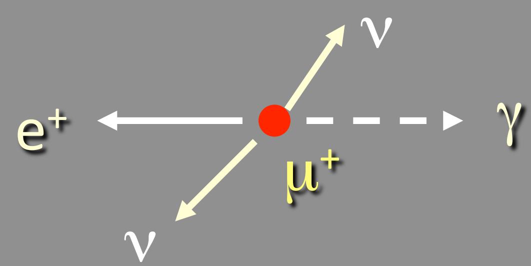
$\theta_{e\gamma}$ = 180°

$E_e = E_\gamma$ = 52.8 MeV

$t_e = t_\gamma$

Radiative decay background

$\mu^+ \to e^+\nu\nu\gamma$



Suppressed by

- decay kinematics
- energy, angle resolution

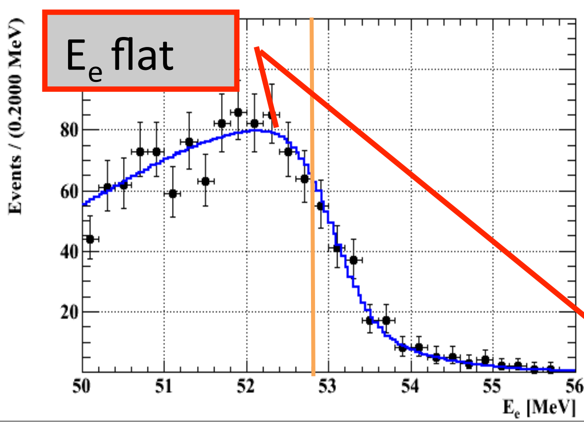
Accidental background

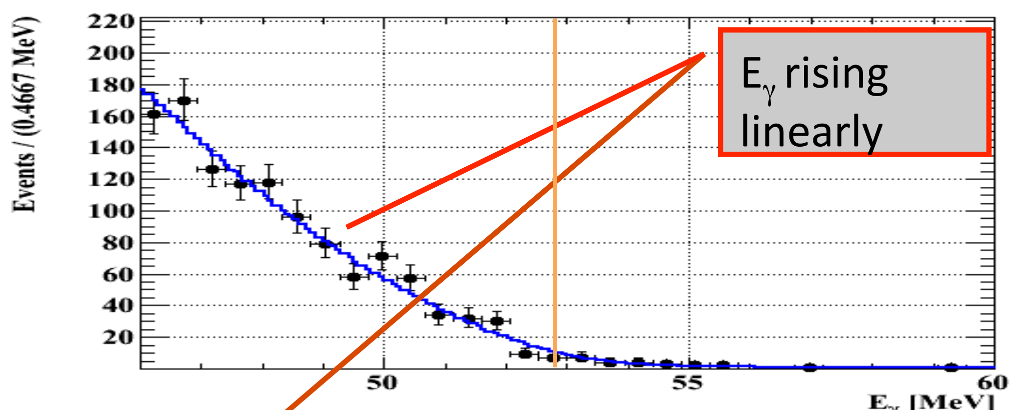
$\mu^+ \to e^+\nu\nu$
+
$\mu^+ \to e^+\nu\nu\gamma$ or $e^+e^- \to \gamma\gamma$

Suppressed by

- Timing, energy, angle resolution

Dominates background at rates needed to reach 10^{-13}

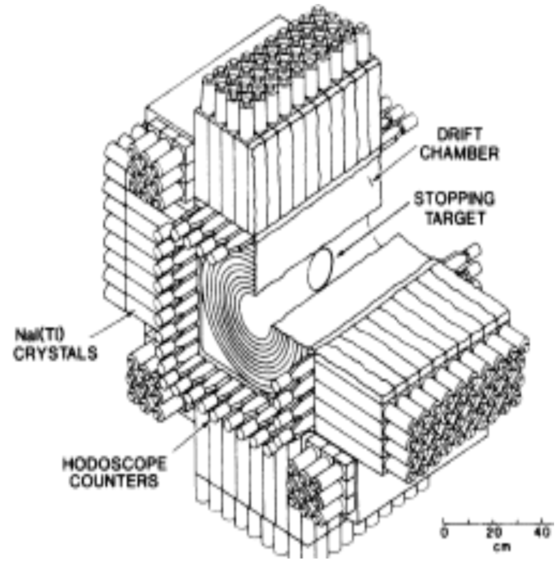


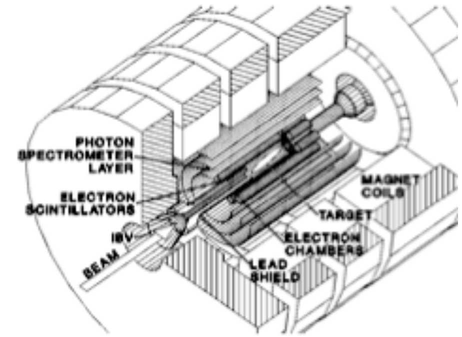


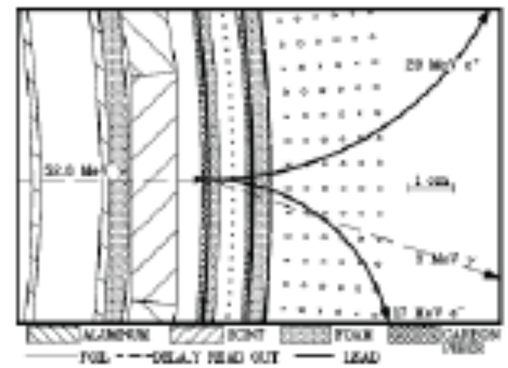
Bknd/signal proportional to $(\delta E_e)^1 \times (\delta E_\gamma)^2 \times (\delta\theta_{e\gamma})^2 \times (\delta t_{e\gamma}) \times$ Rate

Previous Experience and MEG Goal

- Photon energy:
  - Calorimetric (Crystal Box, MEG)
    - Limited by resolution of calorimeter
    - Large solid angle
    - Possibly poor γ direction measurement
  - Pair produce, measure e^+e^- (MEGA)
    - Low acceptance due to thin convertor to reduce energy loss – high rates
    - Very good energy resolution possible
- Positron energy:
  - Calorimetric (Crystal Box)
    - Large solid angle, poor resolution
  - Magnetic spectrometer (MEGA



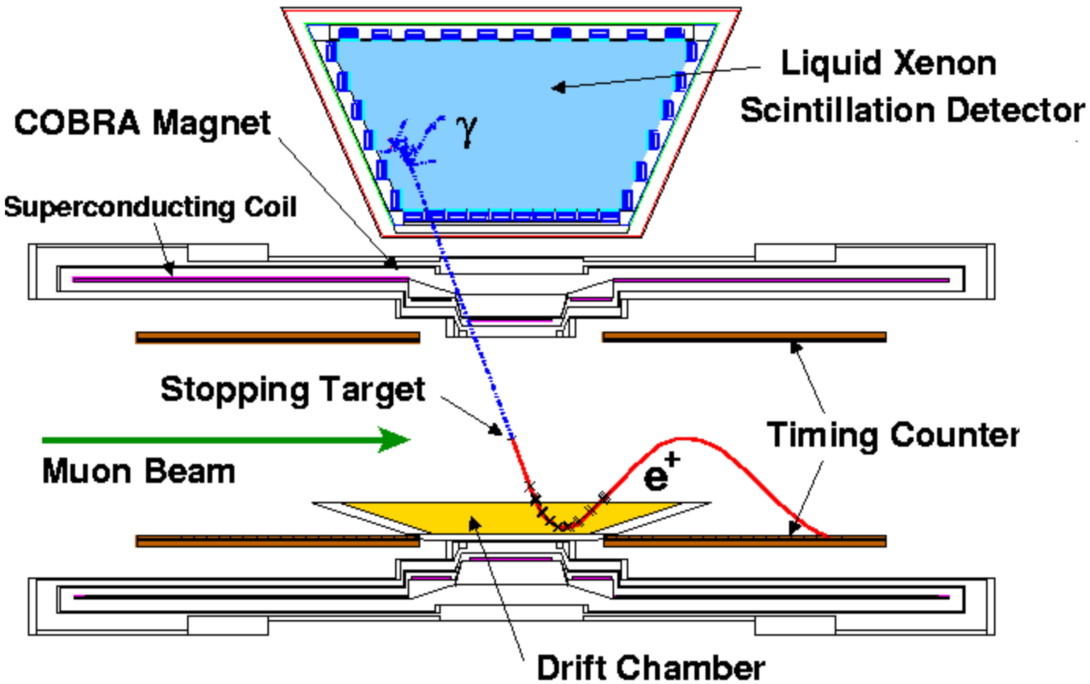


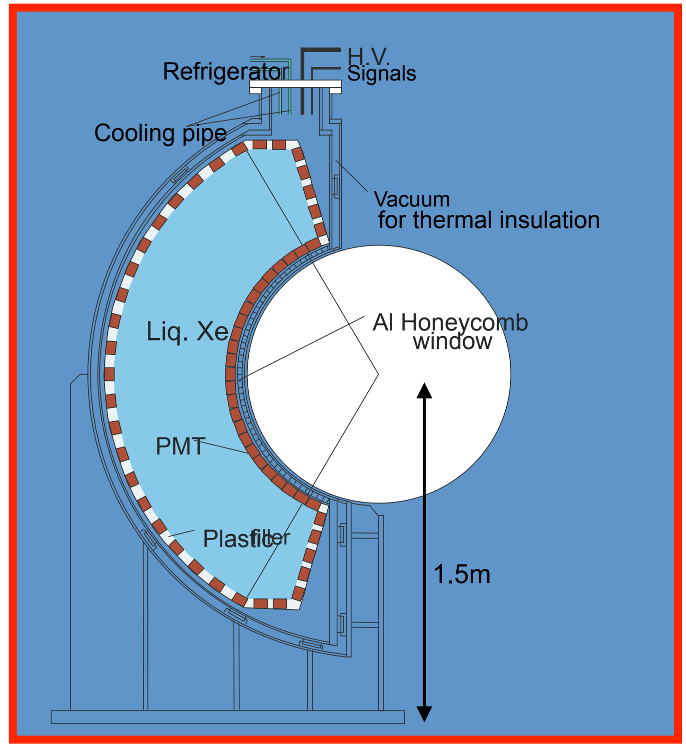


$$\text{Bknd/Sig} = k \times \delta E_e \times \delta E_\gamma^{\,2} \times \delta\theta_{e\gamma}^{\,2} \times \delta t_{e\gamma} \times \text{Rate}$$

Exp./Lab	Year	σ_{RMS} Resolutions				Stop rate [MHz]	Duty cycle [%]	BR (90% CL)
		E_e [%]	E_γ [%]	Δt_{eg}[ps]	$\Delta\theta$[mrad]			
SIN (PSI)	1977	3.7	4.0	590	-	0.5	100	3.6×10^{-9}
TRIUMF	1977	4.3	3.7	2900	-	0.2	100	1×10^{-9}
LANL	1979	3.7	3.4	810	16	0.24	6.4	1.7×10^{-10}
Crystal Box	1986	3.4	3.4	550	37	0.4	(6.9)	4.9×10^{-11}
MEGA	1999	0.51	1.9	610	7	250	(6.7)	1.2×10^{-11}
MEG prop.	2010	0.38	1-2%	64	8	30	100	1×10^{-13}

Liquid Xenon Calorimeter

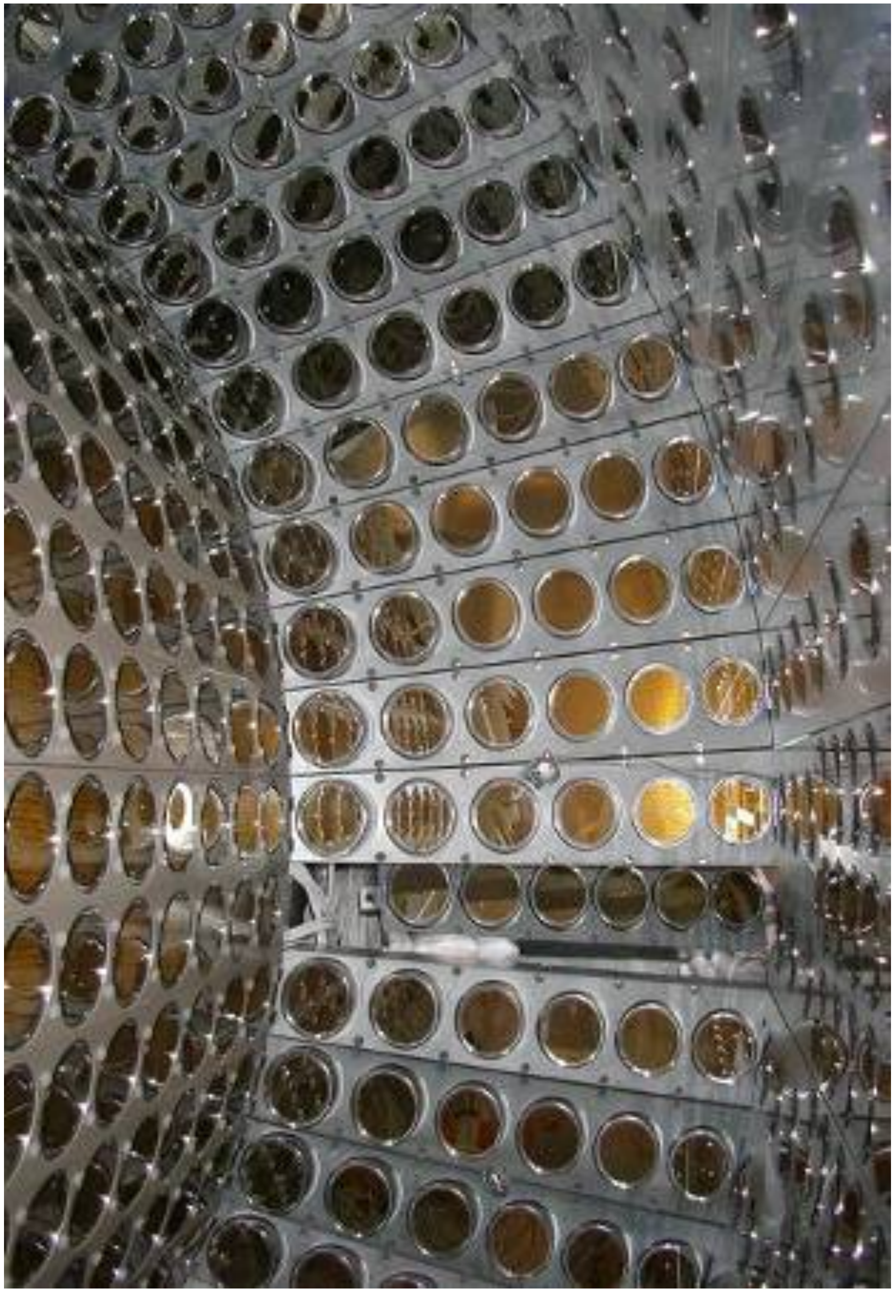




- Relatively high light yield, uniform response
- No self-absorption of scintillation light: attenuation only from impurities
- ~1000 l liquid xenon (largest LXe volume)
- ~860 mesh phototubes on surface, in LXe
- Thin window to reduce photon conversions
- Goal is to measure photon properties:
  - Position: σ_{RMS} = 5 mm
  - Time: σ_{RMS} = 60 ps
  - Energy: σ_{RMS} = ~900 keV at 52 MeV

Density	2.95 g/cm^3
Boiling and melting points	165 K, 161 K
Energy per scintillation photon	24 eV
Radiation length	2.77 cm
Decay time	4.2, 22, 45 ns
Scintillation light wave length	175 nm
Scintillation light absorption length	> 100 cm
Attenuation length (Rayleigh scattering)	30 cm
Refractive index	1.74

MEG Liquid Xenon Calorimeter Calorimeter



Calorimeter Reconstruction Algorithms

- Energy
  - based on properties of the calorimeter
    - Light production is uniformly proportional to energy deposition
    - Light attenuation length is very long (>2 m)
    - Scattering length is relatively short (< 50 cm)
    - Photocathode coverage is relatively uniform
    - Phototube quantum efficiency and gain can be well measured and equalized
  - First estimator of energy is sum of signals in phototubes (corrected for gain and quantum efficiency), corrected by local photocathode fractional coverage
  - Additional energy correction factors determined as a function of 3D position using extensive data with photons from π^0 decay
    - Corrections vs. conversion point due to large variations of photocathode coverage with position when conversion is near the front face
    - Corrections vs. transverse coordinate due to geometrical effects (shallow angle of incidence on phototube face …)
- Time
  - Fit that is basically a weighted average of times in phototubes, corrected for propagation time from shower position to phototube – primarily from front face
  - Time at the vertex corrected for 53 MeV photon propagation time to first conversion point and for optical photon propagation to phototube – 5 mm error in depth of conversion is about 50 ps error in flight time
- Position
  - Fit to pattern of signal amplitudes in phototubes, primarily on front face

Advantages and Disadvantages of Liquid Xenon Calorimeter

- Advantages
  - Uniform ratio of light produced to energy deposited – fluctuations in fraction of ionization vs. light contributes to resolution at low energy if both are not measured
  - No dead material in active volume
  - High light yield – typically ~200k photo-electrons for 53 MeV photon
  - Signal is fast – decay time ~50 ns
  - Very long absorption length limited by impurities
  - Can fit for vertex position in all dimensions – important in determining photon time at vertex

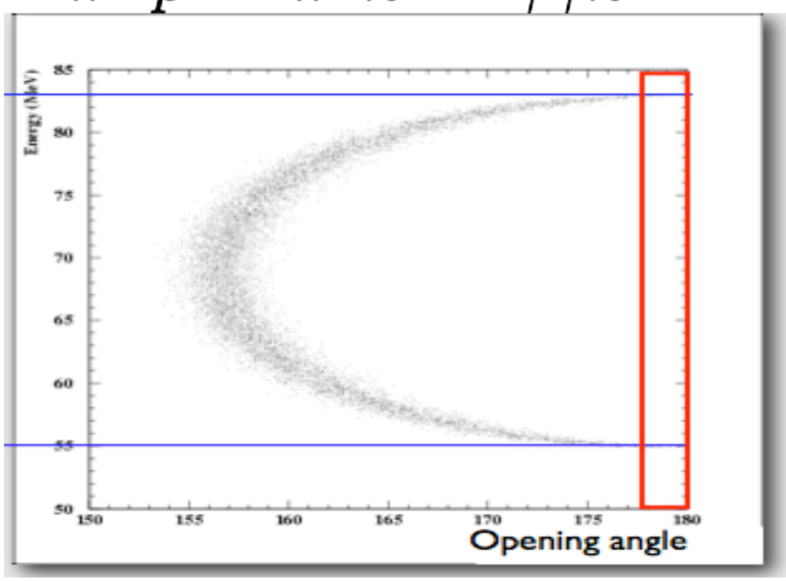
- Disadvantages
  - Lack of optical separation means pileup is not easily isolated and affects signals far away
  - Relatively short scattering length means light paths can be complicated, with reflections important to observed light distribution
  - Need for cryostat reduces acceptance due to photon conversions in the cryostat wall
  - Granularity of photocathode coverage on the walls complicates position and energy reconstruction for showers near the wall
  - Calibrating each photo-detector for quantum efficiency times gain is arguably more difficult than it is for isolated detector elements

Calibration and Resolution Measurement Schemes

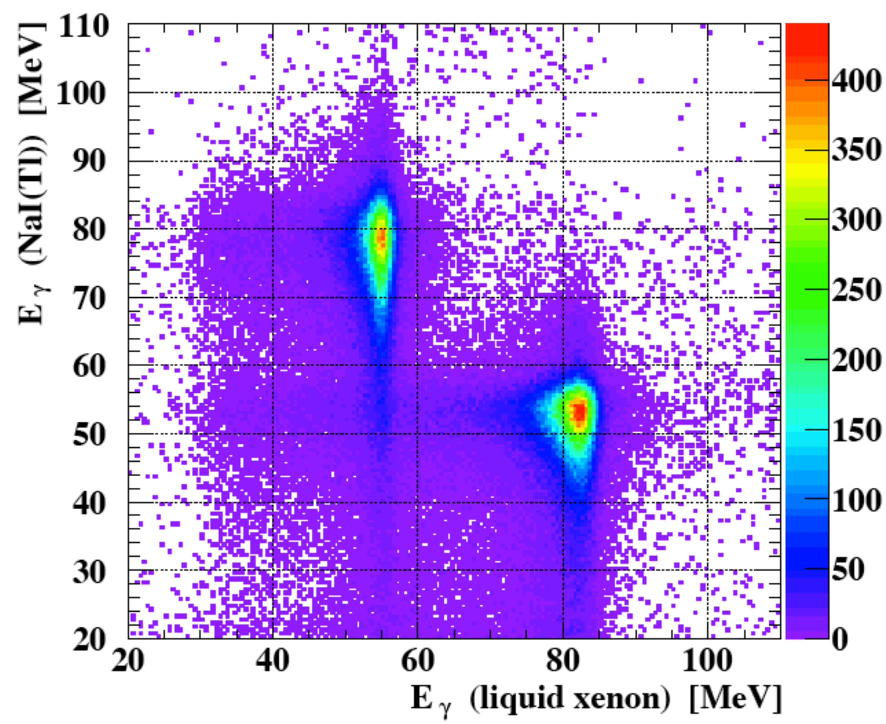
- Energy
  - Primary energy scale calibration and resolution from pion charge exchange: π^- capture on protons at rest, producing a π^0 with low, fixed momentum
  - Monitoring with photons of fixed energy from nuclear reactions
  - Phototube quantum efficiency from alpha sources in calorimeter
  - Phototube gain from LEDs
- Time
  - Alignment from pion charge exchange data with a reference scintillator
  - Resolution from same data, de-convolving reference scintillator resolution and finite target size effects
- Position
  - Alignment by survey and by imaging small collimators placed in front of the calorimeter at known positions
  - Resolution by fit to shape of edges of collimator, referenced to Monte Carlo

E_γ Calibration

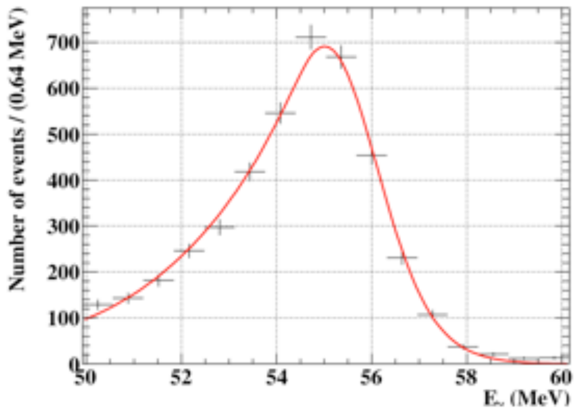
$$\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$$



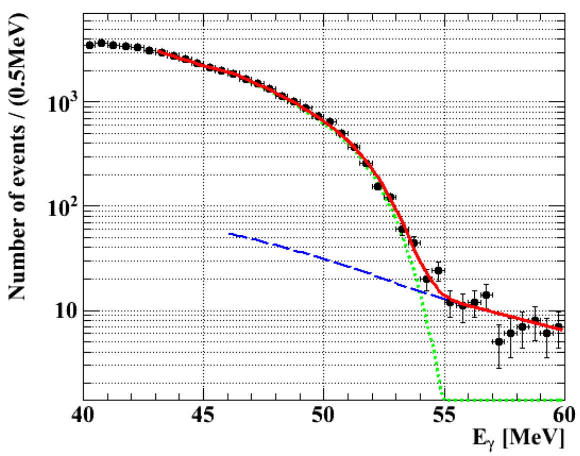
- Negative pions stopped in liquid hydrogen target
- Tagging the other photon at 180° provides monochromatic photons in calorimeter
- Data are used to set absolute energy scale vs. position in calorimeter (in 3D)
- Resolution also measured vs. position in 3D
- Dalitz decays were used to study positron-photon synchronization and time resolution:



Photon Energy Resolution from Charge Exchange

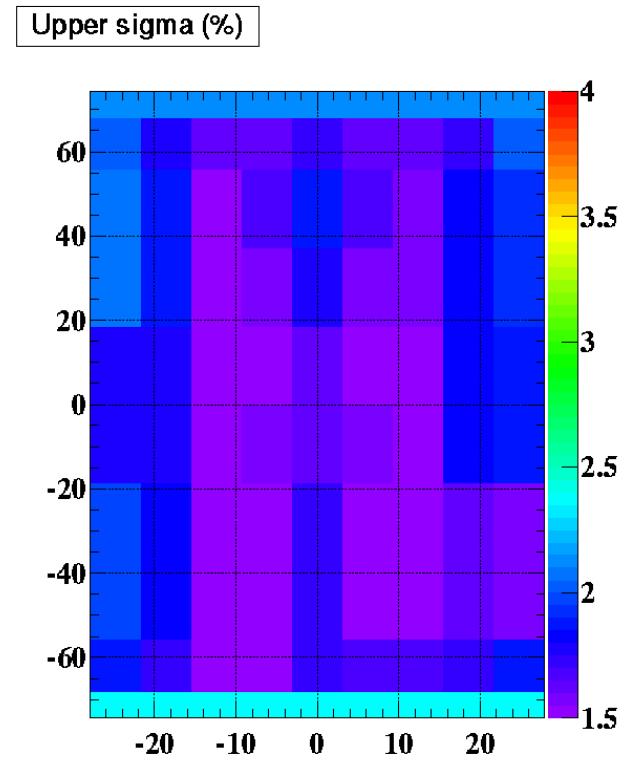


Representative photon resolution function

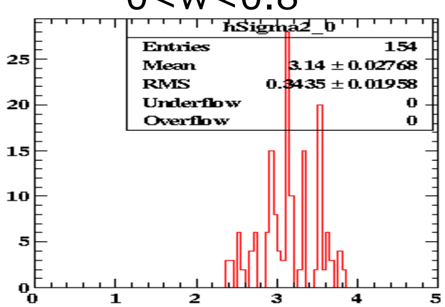


Cross check with fit to distribution of radiative decay photons

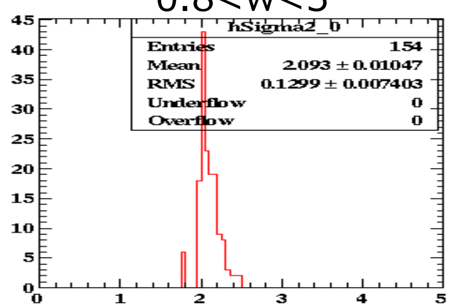
Variation of fitted resolution with transverse position in calorimeter



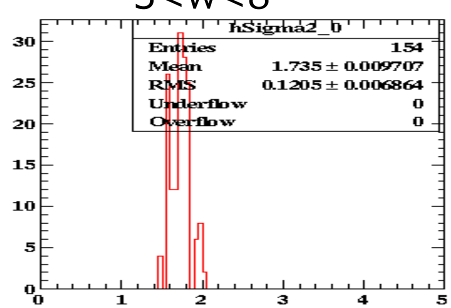
0<w<0.8



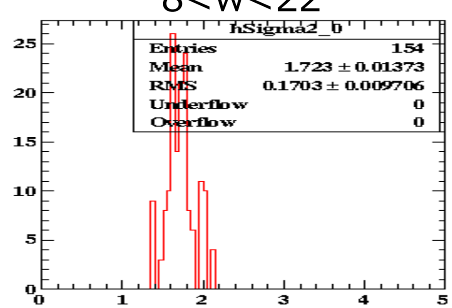
0.8<w<3



3<w<8



8<w<22

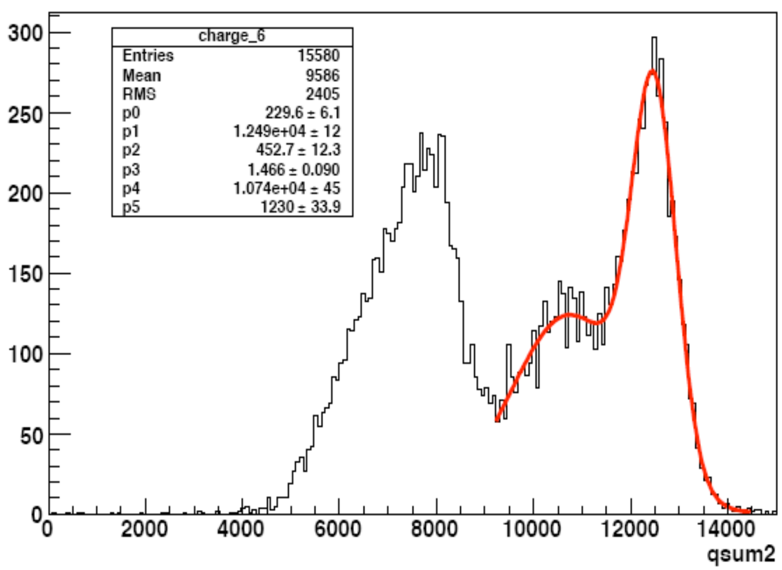


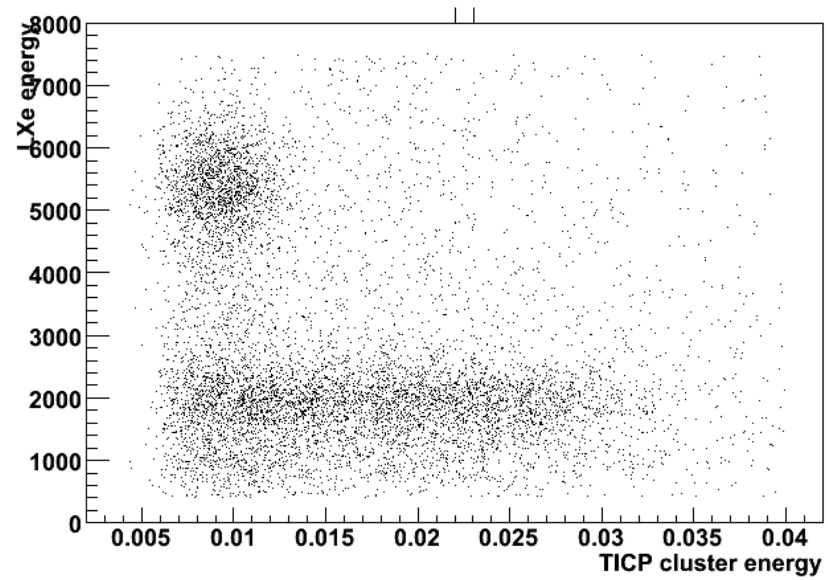
Variation of fitted resolution with shower depth

LXe Calibration Monitoring using Photons from Nuclear Interactions

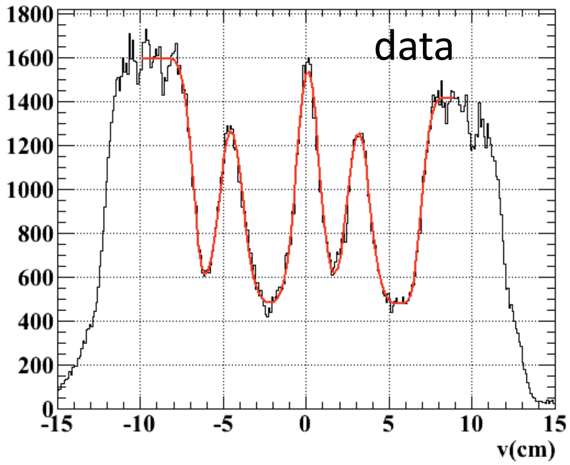
- Cockcroft Walton proton accelerator
  - 300-1000 keV, high flux
  - Beam line that allows remote insertion of thin foil target in vacuum to center of apparatus
  - Produce photons by nuclear reactions on thin target
  - Calibration run typically 3 times per week

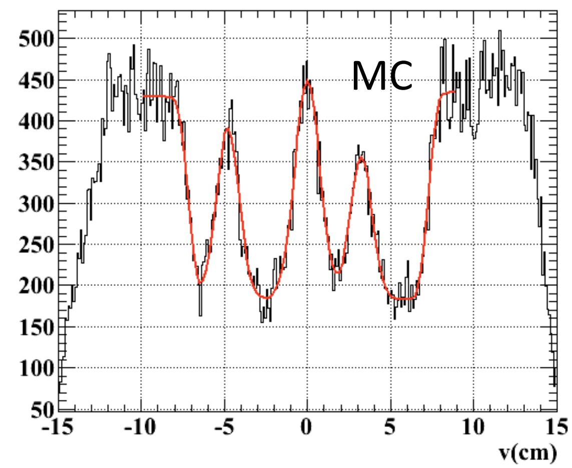
Reaction	E_p [keV]	σ [mb]	E_γ [MeV]	
$p + Li \rightarrow Be + \gamma$	440	5	17.6, 14.6	Resolution, E scale, uniformity
$p + B \rightarrow C + \gamma\gamma$	163	0.2	4.4 + 11.6	Cross-time LXe and timing counter





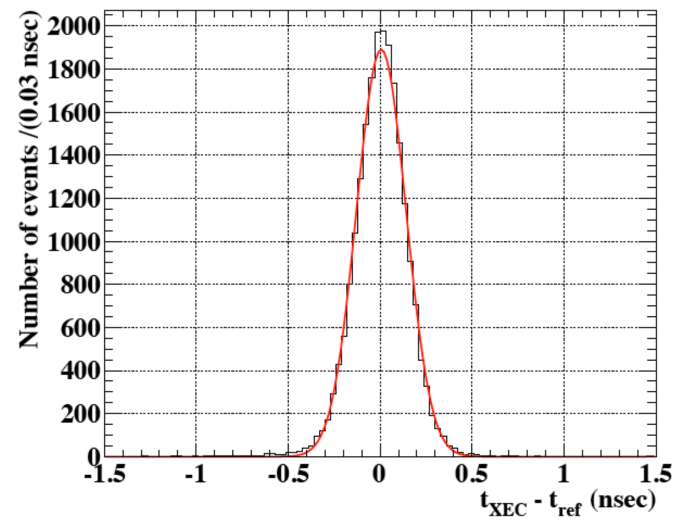
Position and Time Resolution





Pb collimator

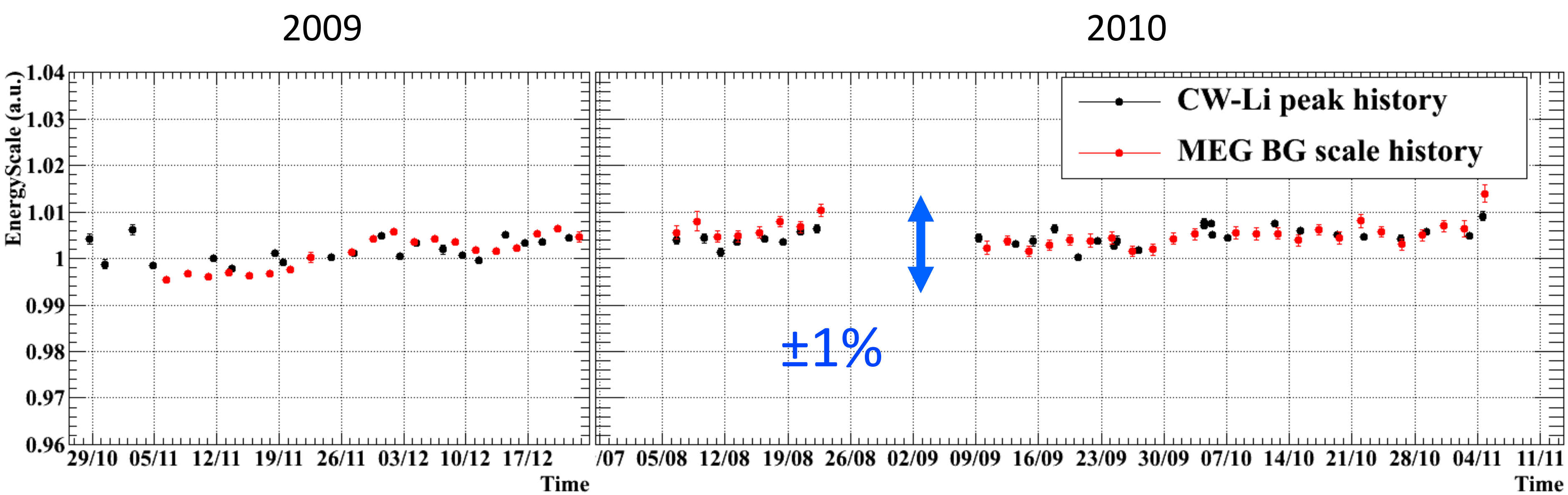
- Image slots in lead collimator in front of calorimeter, using charge exchange data, to align calorimeter
- Same data used to infer resolution: in transverse directions approximately 5 mm



- Measure time in calorimeter with respect to reference counter in charge exchange data
- Fit difference to Gaussian – 135 ps
- De-convolve resolution of reference counter (93 ps) and finite target size (58) gives full calorimeter resolution of 78 ps
- Intrinsic resolution ~45 ps (excluding conversion point contribution) determined by comparing times from two subsets of tubes

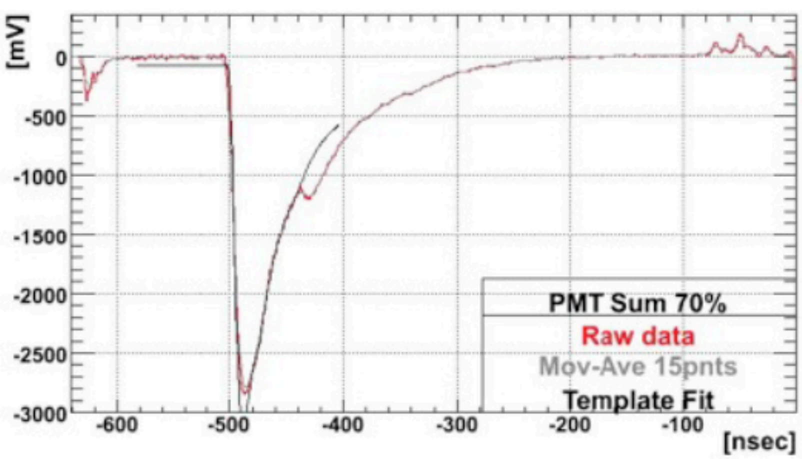
Stability of E_γ Scale

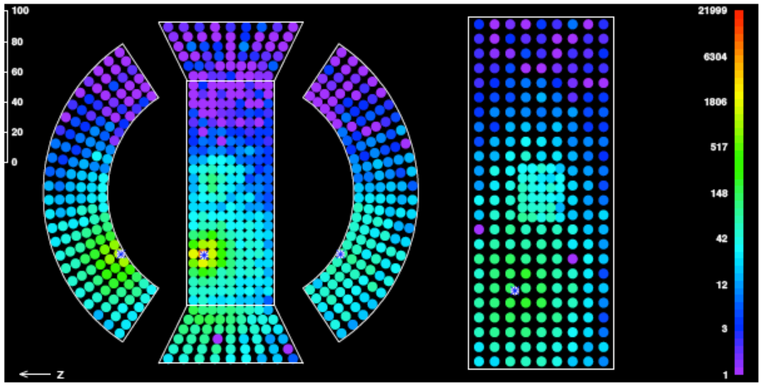
- Stability monitored by variety of measurements
  - Primarily from the photons from nuclear reactions
  - Checks against endpoint of the radiative decay spectrum
  - Checks against cosmic ray spectrum
  - Slow gain shift in photo-tubes calibrated out
- Long-term stability good to 0.3% RMS



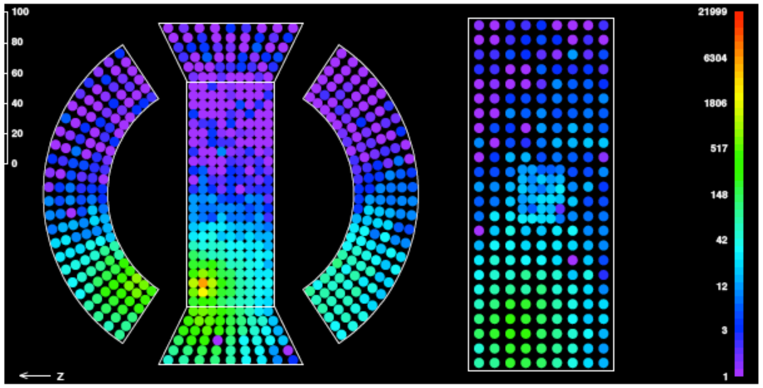
Pileup Removal

- Events with clear pileup signal are identified and handled in a variety of ways
  - Events that have spatially separated showers corrected by removing secondary peak and replacing tube energies with templates based on light in unaffected regions
  - Events that have clear evidence of showers overlapping in time are fit to superposition of pulses of known shape.
  - Events that have evidence of pileup, but without clear separation in time or space are eliminated





before



after

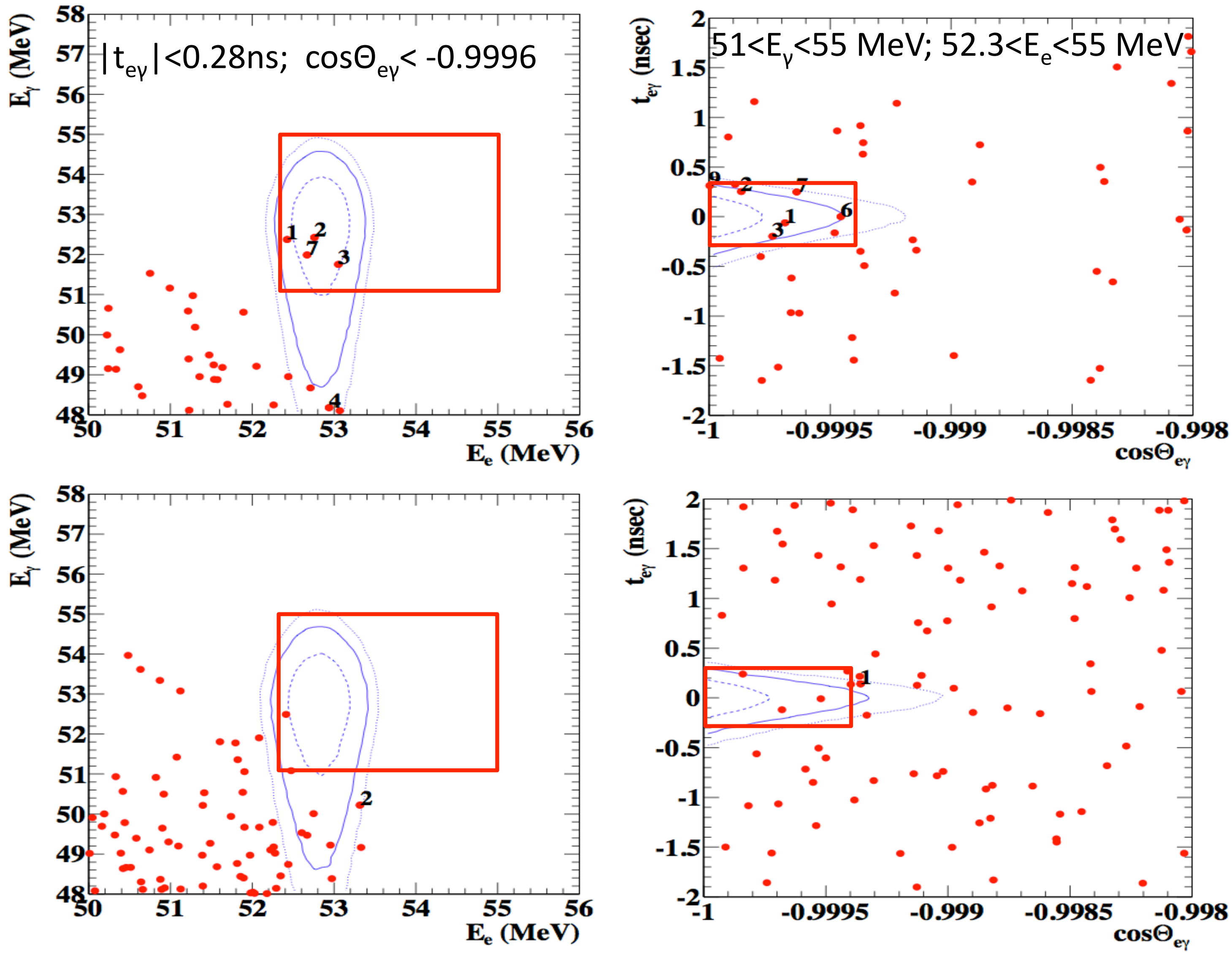
Current MEG Results from Data Through 2010

Order data by likelihood ratio, contours at 1, 1.64, 2σ

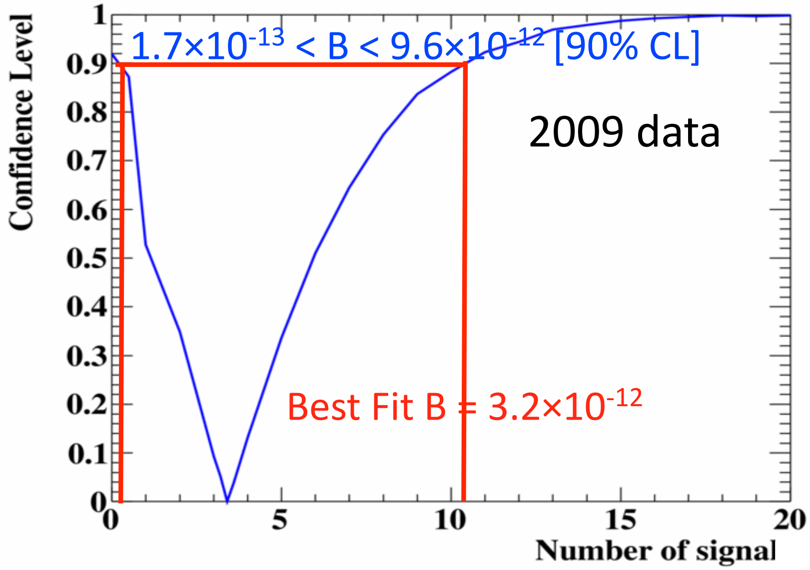
on dt, cos(θ select on Eγ, E_e

2009

2010

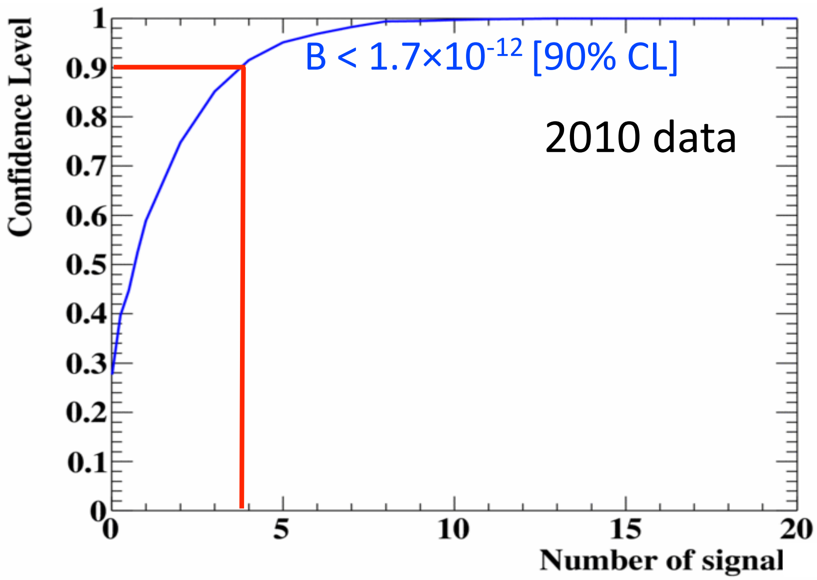


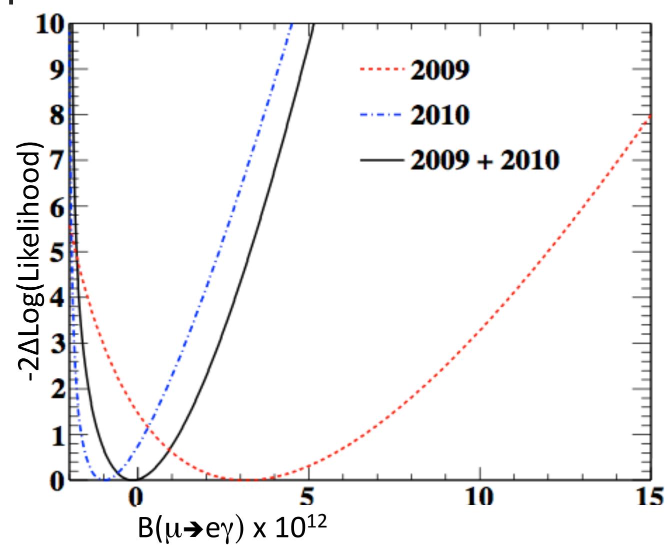
Current MEG Result



	BR(fit)	LL 90% CL	UL 90% CL
2009	3.2×10^{-12}	0.17×10^{-12}	9.6×10^{-12}
2010	-0.99×10^{-13}	--	1.7×10^{-12}
2009+2010	-0.15×10^{-13}	--	2.4×10^{-12}
Expected UL			1.6×10^{-12}

- Systematic errors (in total 2% in UL) include:
  - relative angle offsets
  - correlations in e^+ observables
  - normalization





$B(\mu^+\to e^+\gamma) < 2.4 \times 10^{-12}$ [90% CL]

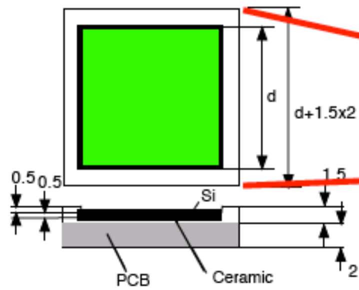
Potential Upgrades to Calorimeter

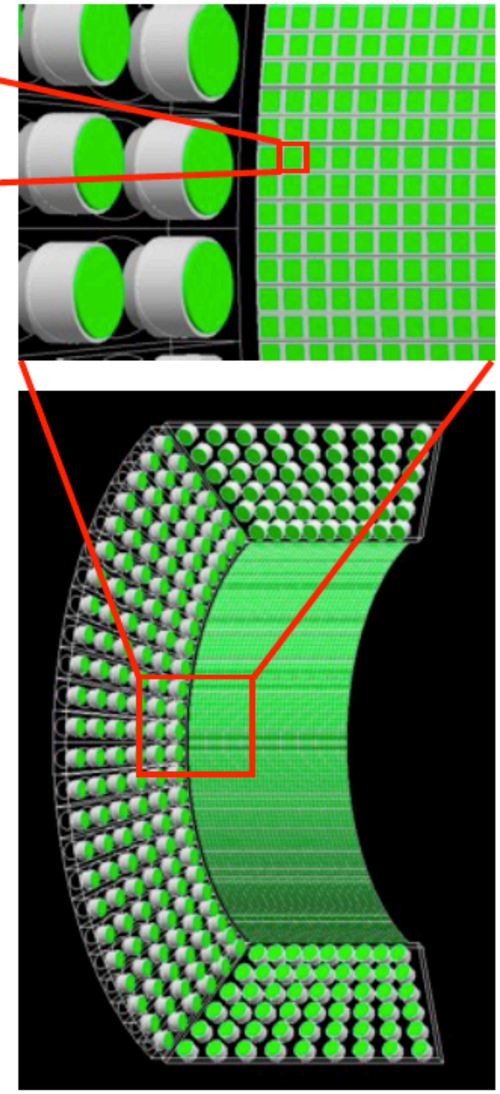
- Limitations to performance
  - Resolution for early conversions worse due mostly to granularity of photo-cathode coverage
  - Resolution near edges worse due to less than optimal pointing geometry of phototubes
  - Stochastic variation of resolution and absolute calibration with 3D position in calorimeter that is not completely understood. Likely due at least in part to quantum efficiency and gain calibration errors.
  - Effects of scattering, particularly with reflections off walls, complicates energy determination and likely contributes to resolution

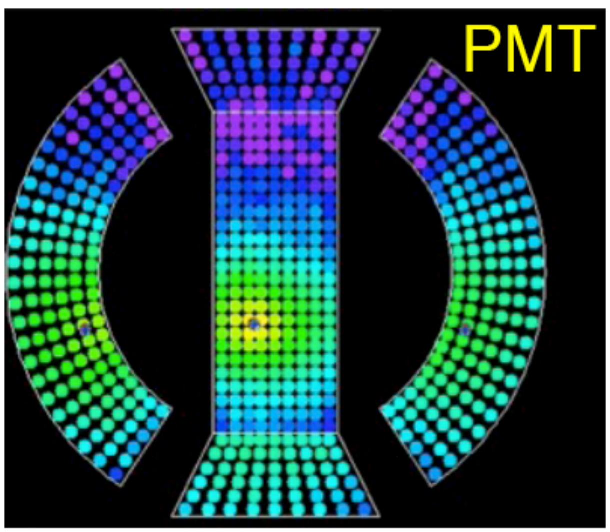
- Upgrades being considered
  - Replace the phototubes on front face with MPPCs (SIPMs)
    - Reduce the granularity of the photo-cathode coverage
    - Possibly increase the photo-cathode coverage
    - Less dead space and material at the front face – increased efficiency
  - Use non-reflective coating on the interior face of the cryostat to reduce reflections
    - Plenty of photo-electrons, so decrease in total light yield is not a problem
    - Will likely improve all of energy, timing, position resolution
  - Modify phototube orientation on side walls to be in a single plane
    - Reduces shadowing
  - Increase active size in the Z direction
    - Improves light collection and resolution

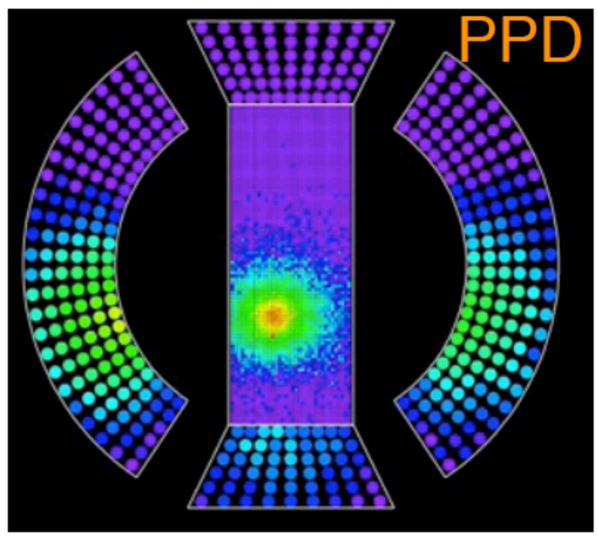
MPPCs for Front Face

- Use large area MPPCs 12x12 mm^2
- A few potential suppliers
- Mount them on ceramic base + printed circuit board
- Up to 3500 devices
- Many things need to be studied
  - Intrinsic non-linearity with large dynamic range – correctible
  - Absorption of vuv photons in protective layer – remove it
  - Reflection from silicon surface – anti-reflective coating
  - Cross-talk between pixels – cut channels
  - After-pulsing, worse at low temperature
  - Potential for increased noise summing many signals



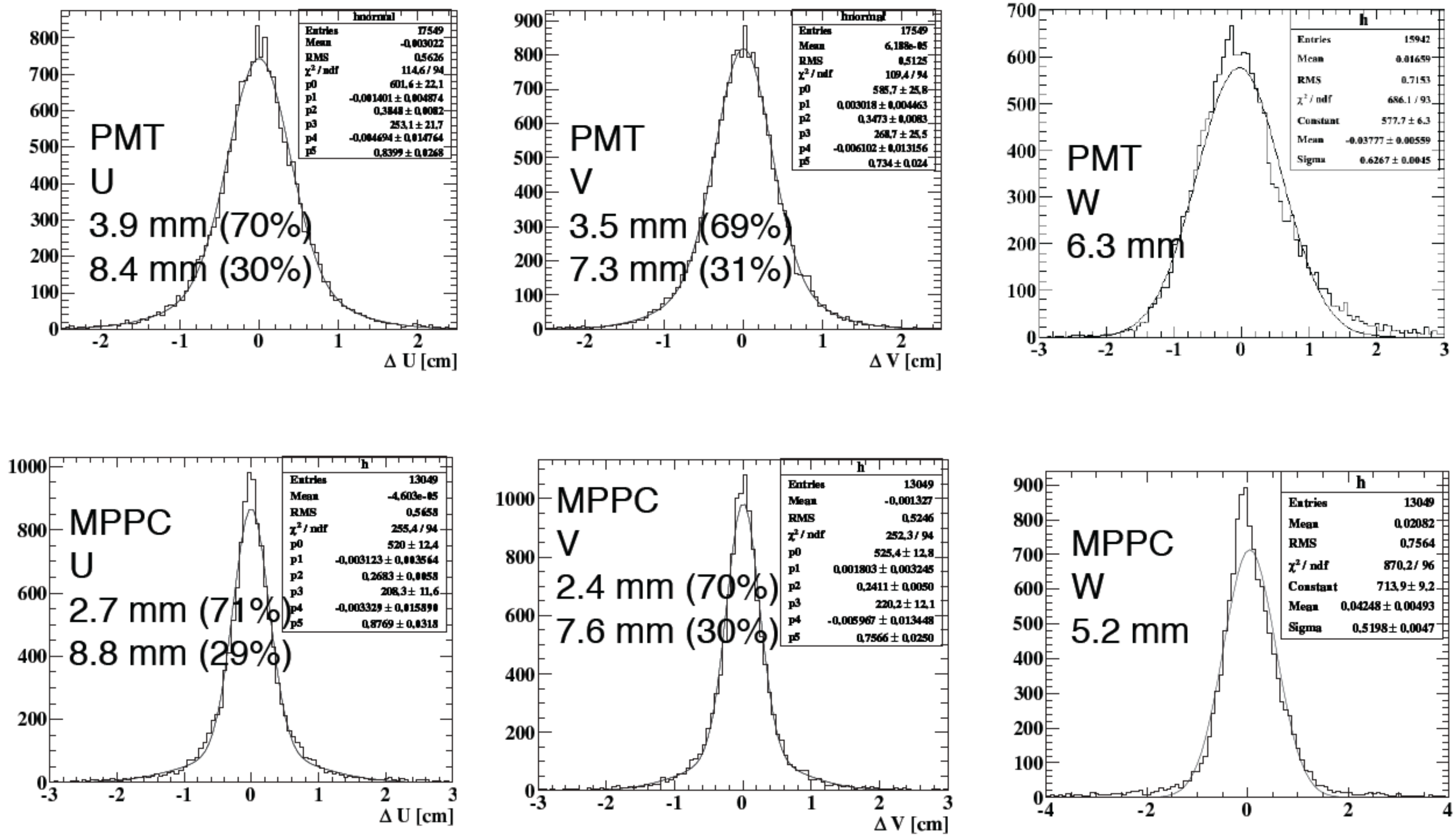




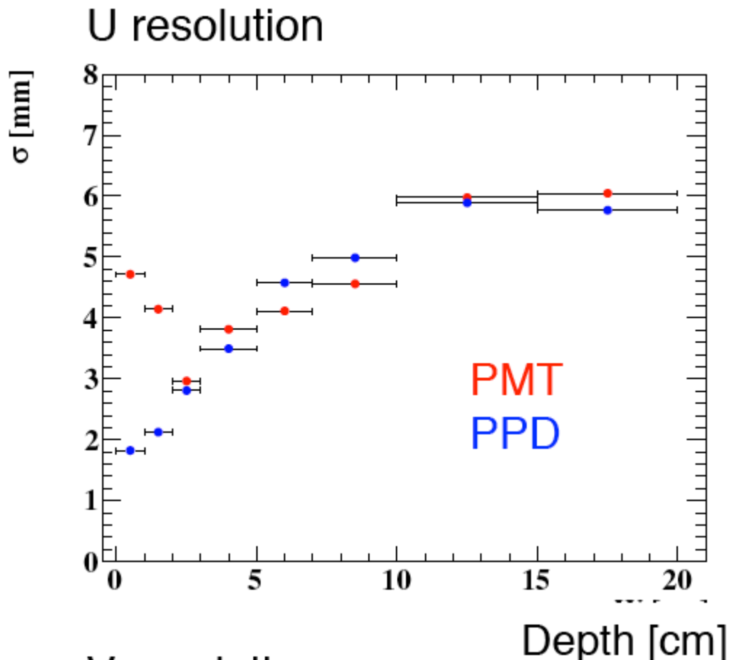


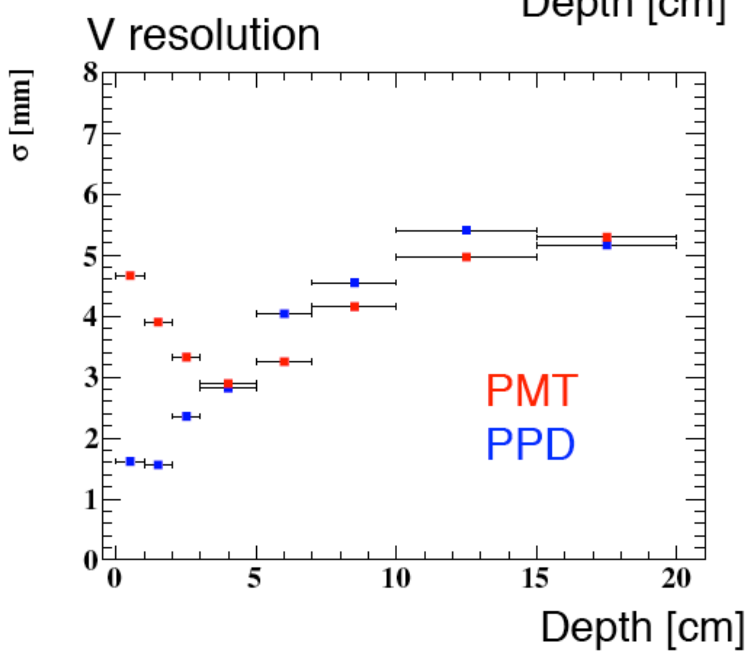
Comparison of Position Resolution

Axial | Azimuthal | Depth

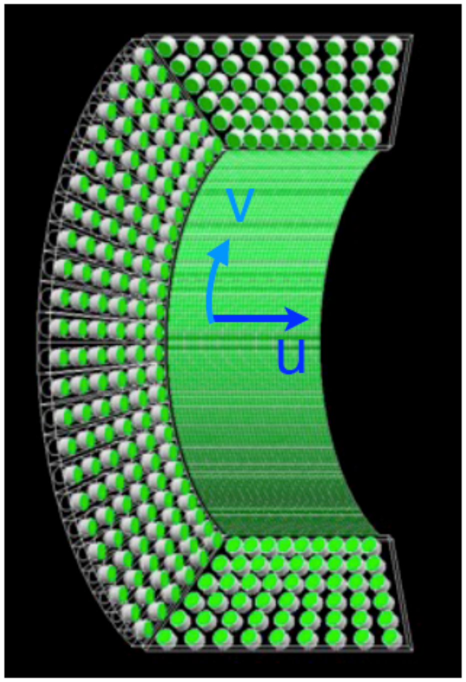


Position Resolution Improvement vs. Depth





depth < 3cm : PPD is better
depth > 3cm : Same resolution

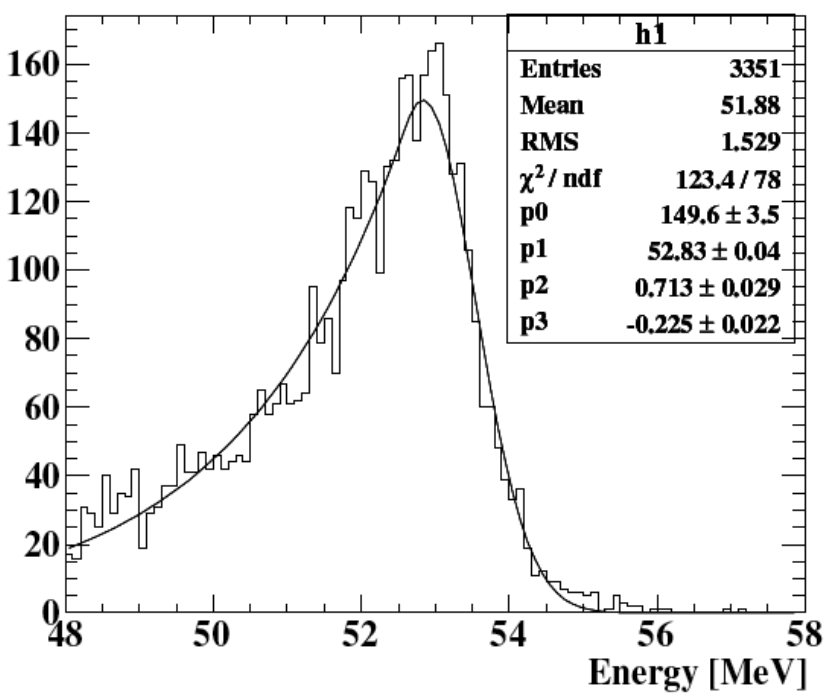


* This analysis is done using true #of p.e.
The same study using waveform yet to be done.

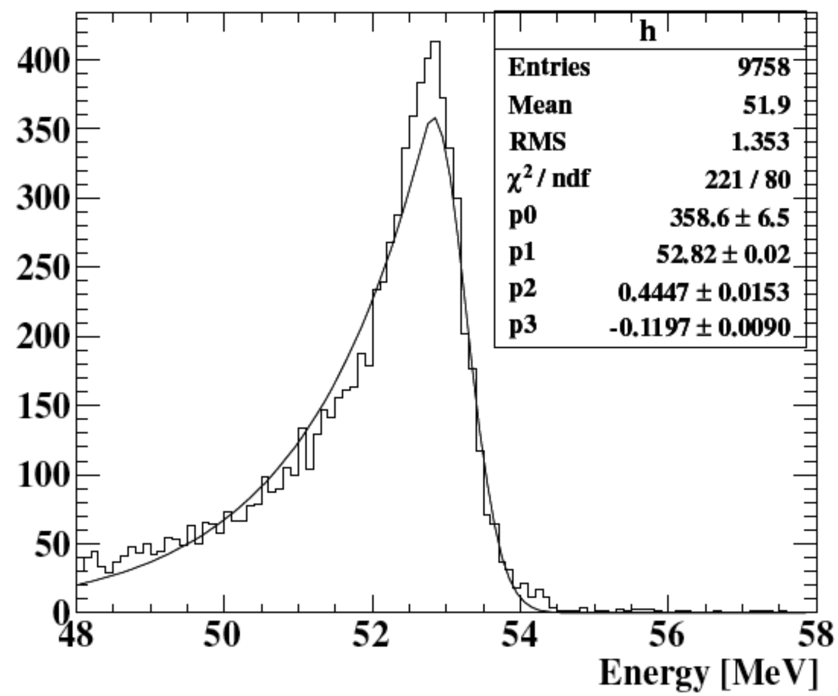
Effect of MPPCs on Energy Resolution

Results from Monte Carlo that includes shower fluctuations and light propagation but not all contributions to energy resolution

Depth < 2cm



Depth > 2cm



$\sigma = 1.3\ \%$

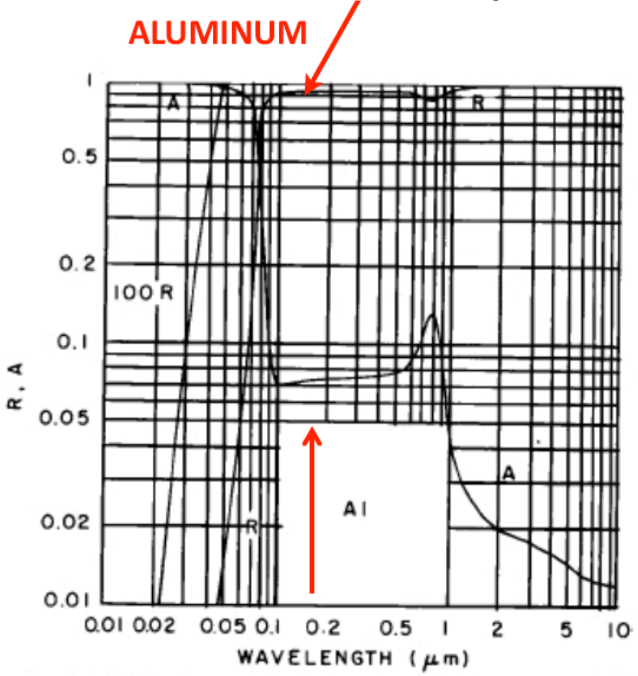
$\sigma = 0.8\ \%$

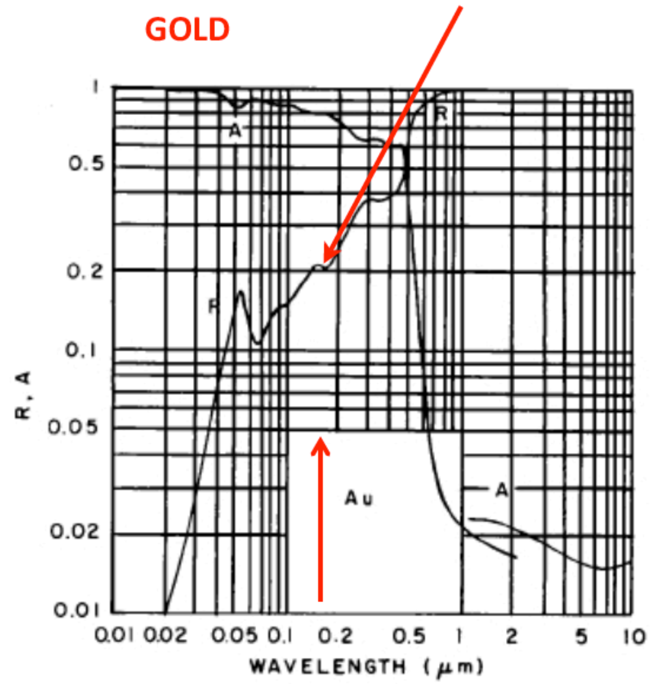
c.f. PMT MC : 2.6%

Almost same as PMT MC

Reduce Reflectivity of Cryostat Walls

- Gold has lower reflectivity at 180 nm

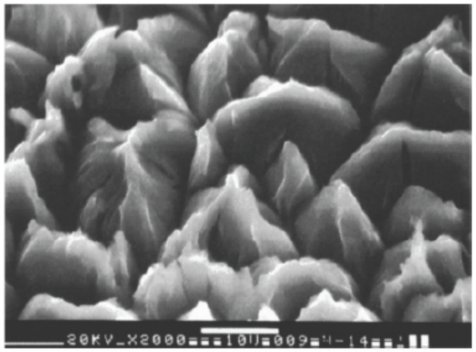




- Anti-reflective coatings from industry

MARTIN MARIETTA ASTRONAUTICS GROUP ("Martin Black") ALUMINUM TREATMENT AND GOLD DEPOSITO ON PEEK SURFACES

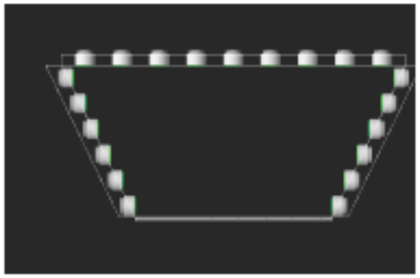
Martin Black. Martin Black is an anodized aluminum surface that is made microrough by a special anodization process developed by Martin Marietta Astronautics Group, Denver (Wade et al., 1978, Shepard, 1992). It is made black from the inclusion of an aniline dye which is sealed into the surface. It was developed for the Skylab program and has been used on a wide variety of space instruments operating from the vacuum ultraviolet to the far-infrared. The surface is rough, and scattering at several fundamentally different scale lengths occurs.



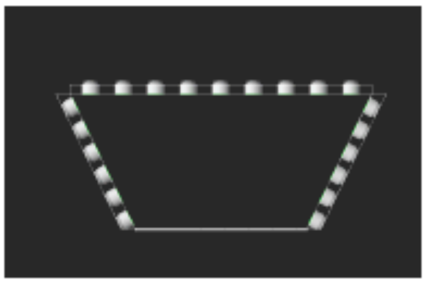
Modify Phototube Orientation, Increase Lateral Size

Motivated by poor light collection efficiency on side faces

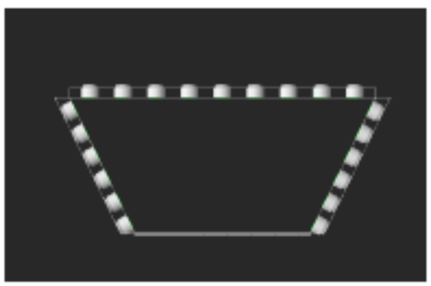
B



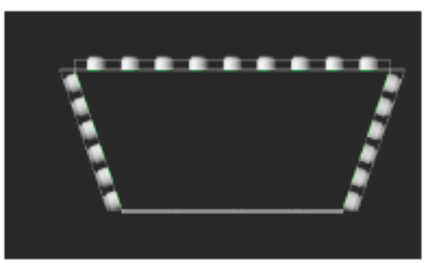
C



D



E



	W < 2cm		w >= 2cm	
	σ_{up}	FWHM	σ_{up}	FWHM
B	0.9%	3.3%	0.7%	2.3%
C	0.8%	3.4%	0.5%	1.4%
D	0.8%	3.2%	0.5%	1.4%
E	0.6%	3.0%	0.5%	1.3%

Summary

- MEG is background limited above 10^{-12} branching fraction largely due to resolutions worse than proposal values
- Nonetheless, should reach a 90% CL sensitivity below 10^{-12} with data to be collected through ~1 year from now
- We are considering upgrades that could improve resolutions (and hence background rejection) and that could be implemented within ~2 years and yield significantly improved sensitivity within 5 years
  - Upgraded liquid xenon calorimeter – discussed here
  - New drift chamber – improved energy, angle measurements
  - New timing counters – improved intrinsic resolution, better match to drift chamber
  - Possible active target – improved angle determination
  - Muon stop rate increase by up to a factor of 3
- We plan to submit a proposal for the upgrades by the end of the year